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Intensity fluctuations of partially coherent laser beam arrays in weak atmospheric turbulence

Ç. Arpali · S.A. Arpali · Y. Baykal · H.T. Eyyuboğlu

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Abstract The intensity fluctuation of a partially coherent laser beam array is examined. For this purpose, the on-axis scintillation index at the receiver plane is analytically formulated via the extended Huygens–Fresnel diffraction integral in conditions of weak atmospheric turbulence. The effects of the propagation length, number of beamlets, radial distance, source size, wavelength of operation and coherence level on the scintillation index are investigated for a horizontal propagation path. It is found that, regardless of the number of beamlets, the scintillation index always rises with an increasing propagation length. If laser beam arrays become less coherent, the scintillation index begins to fall with growing source sizes. Given the same level of partial coherence, slightly less scintillations will occur when the radial distance of the beamlets from the origin is increased. At partial coherence levels, lower scintillations are observed for larger numbers of beamlets. Both for fully and partially coherent laser beam arrays, scintillations will drop on increasing wavelengths.

Ç. Arpali · S.A. Arpali (✉) · Y. Baykal · H.T. Eyyuboğlu
Electronic and Communication Engineering Department,
Çankaya University, Öğretmenler Cad. No:14 Yüzüncüyıl,
06530 Balgat Ankara, Turkey
e-mail: saltay@cankaya.edu.tr
Fax: +90-312-2848043

Ç. Arpali
e-mail: c.arpali@cankaya.edu.tr

Y. Baykal
e-mail: y.baykal@cankaya.edu.tr

H.T. Eyyuboğlu
e-mail: h.eyyuboglu@cankaya.edu.tr

1 Introduction

Within the past decade, laser beam arrays have been commonly examined due to their advantages such as compactness, efficiency and reliability in high power systems [1]. There is also a substantial interest in finding the benefits of using such arrays in free space optic communication links [1–11]. Most of these studies mainly cover the propagation properties of laser beam arrays such as their intensity [2], average intensity [4–10], scintillation index [10, 11] and beam propagation factor [1–3, 9, 10]. By using the phase-locked [1] or non-phase-locked [2] method, coherent [3, 9, 10] or incoherent [7, 10] off-axis laser beams can be combined in different forms of laser array such as radial arrays [1, 2, 4, 8, 11], rectangular arrays [4–7] and ring distributed arrays [3, 9, 10]. In general, the type of laser beam used in a specific application directly affects the system performance [4–11]. In other words, the propagation medium of an optic link has a different degradation effect on different beam types. Optical turbulence is one of the major causes of deleterious effects on laser beam propagation, and it is associated with random variations of the refractive index both in time and space, causing beam wander and irradiance fluctuations (scintillation) at the receiver plane [12]. The scintillation index causes signal fading and results in higher bit error rates, in applications such as astronomical imaging, remote sensing and optical communications that require the transmission of modulated laser beams through the atmosphere. To eliminate the destructive effect of scintillation on laser beam transmission different methods are used, among them increasing receiver aperture size [13], making phase correction via adaptive optics [14, 15], employing different beam types [16] and using partially coherent light sources [17]. Because of certain advantages of using partially coherent beams in optical communications [18, 19] there has been a concerted attempt to explore some statistical moments of such beams like spreading [20], transmittance [21], power [22], polarization [23], average intensity [17, 24–27] and scintillation [18, 23, 28, 29]. Despite the greater spreading created by the partial coherence property, it has been shown that in terms of scintillations, partially coherent beams in the turbulent atmosphere are less affected than fully coherent ones as verified both theoretically [5–7, 18, 28, 29] and experimentally [30]. In this study we focus only on the effects of the scintillations index. Within the different beam types, partially coherent laser beam arrays are also of interest [5–7, 30]. However, most of these studies are restricted to irradiance distributions of laser beam arrays. The scintillation index of partially coherent laser beam arrays in turbulent atmosphere has not been investigated so far. The purpose of this paper is to find on-axis irradiance fluctuations of partially coherent laser beam arrays at the receiver plane in conditions of weak atmospheric turbulence. Starting from the extended Huygens–Fresnel diffraction integral, the scintillation index is formulated as a normalized variance of irradiance fluctuations. Scintillation index calculations in weak fluctuations can also be performed with the Rytov approximation [11, 16, 18, 31, 32]. The Rytov approximation mostly requires numerical integration, sometimes involving excessive computation time, and also it is inadequate in yielding results for the scintillations of partially coherent sources in conditions of weak turbulence [28, 33]. Recently, Eyyuboğlu et al. studied the scintillations of laser array beams using the Rytov method [11]. However, in the literature there is also a good deal of attention given to the Huygens–Fresnel method for evaluating the scintillation index [28, 29, 34] of partially coherent beams. Our aim in the present paper is to investigate the scintillation properties of partially coherent laser beam arrays in weak atmospheric conditions by using the extended Huygens–Fresnel method. Here we focus on the effect of the propagation length, number of beamlets, radial distance, source size, wavelength of operation and coherence level on the scintillation index in a horizontal path. The scintillation advantages of laser beam arrays in turbulent atmosphere are discussed comprehensively. Our scintillation formulation for the partially coherent beam array field presented in this paper can be useful for optical communication links and optical imaging systems.

2 Formulation

The source field expression of the laser beam array is established by N beamlets as [4, 11]

$$u(s_x, s_y) = \sum_{n=1}^{N} \exp\{-k\alpha_n[s_x^2 + s_y^2 - 2r_o(s_x \cos\varphi_n + s_y \sin\varphi_n - 0.5r_o)]\}, \tag{1}$$

where $k = 2\pi/\lambda$ is the wave number, with λ being the wavelength. $\alpha_n = 1/2k\alpha_{sn}^2$ with α_{sn} denoting the Gaussian source size of the nth beamlet. s_x and s_y are the x and y components of the source plane vector. r_o is the transverse radial distance between the on-axis point of the source plane and the peak of the nth beamlet, and $\varphi_n = 2\pi(n-1)/N$ is the angle between the s_x axis and r_o. Also we note that (1) stands for the phase-locked combination of the radial laser beam array [4]. To convert the source beam formulation of (1) into a partially coherent laser beam array, we follow the procedure outlined in Ref. [29]. According to the extended Huygens–Fresnel principle, the on-axis scintillation index is found by

$$m^2 = \langle I^2(L)\rangle / \langle I(L)\rangle^2 - 1, \tag{2}$$

where $I(L) = u(L)u^*(L)$ and $\langle I(L)\rangle = \langle u(L)u^*(L)\rangle$ are the on-axis instantaneous intensity and the on-axis average intensity on the receiver plane, respectively, $u(L)$ is the on-axis optical field on the receiver transverse plane, found via the extended Huygens–Fresnel principle, * indicates the complex conjugate, $\langle\rangle$ refers to the ensemble averaging, L is the propagation length from the source plane to the receiver plane.

$\langle I(L)\rangle^2$ and $\langle I^2(L)\rangle$ are retrieved using steps described in Ref. [29]. In this way, the on-axis average intensity for the partially coherent laser beam array will become

$$\langle I(L)\rangle = \frac{\pi^2}{(\lambda L)^2} \sum_{n=1}^{N} \sum_{m=1}^{N} \frac{1}{t_1^2 t_2^2} \exp[-kr_o^2(\alpha_n + \alpha_m^*)] \times \exp\left(\frac{q_{2x}^2 + q_{2y}^2}{4t_2^2}\right) \exp\left(\frac{k^2 r_o^2 \alpha_n^2}{t_1^2}\right), \tag{3}$$

here

$$t_1^2 = k\alpha_n + \frac{1}{\rho_0^2} + \frac{1}{4\rho_s^2} - \frac{ik}{2L}, \quad t_2^2 = k\alpha_m^* + \left(\frac{1}{\rho_0^2} + \frac{1}{4\rho_s^2}\right) + \frac{ik}{2L} - \frac{1}{t_1^2}\left(\frac{1}{\rho_0^2} + \frac{1}{4\rho_s^2}\right)^2,$$

$$q_{2x} = 2kr_o\alpha_m^* \cos\varphi_m + \frac{2kr_o\alpha_n \cos\varphi_n}{t_1^2}\left(\frac{1}{\rho_0^2} + \frac{1}{4\rho_s^2}\right),$$

$$q_{2y} = 2kr_o\alpha_m^* \sin\varphi_m + \frac{2kr_o\alpha_n \sin\varphi_n}{t_1^2}\left(\frac{1}{\rho_0^2} + \frac{1}{4\rho_s^2}\right),$$

where ρ_s is the degree of source coherence, $\rho_0 = (0.545C_n^2 k^2 L)^{-3/5}$ is the coherence length of a spherical wave propagating in the turbulent medium, with C_n^2 being the structure constant [17]. Similarly, the average of the squared on-axis instantaneous intensity of the partially coherent laser beam array is obtained as

$$\langle I^2(L)\rangle = \sum_{j=1}^{3} Y_j, \tag{4}$$

where

$$\begin{aligned}
Y_j = {} & \frac{E_j \pi^4}{(\lambda L)^4} \sum_{n=1}^{N}\sum_{m=1}^{N}\sum_{\ell=1}^{N}\sum_{o=1}^{N} \frac{1}{\beta_{j1}^2\beta_{j2}^2\beta_{j3}^2\beta_{j4}^2} \exp\left(\frac{q_{j4x}^2}{4\beta_{j4}^2}\right) \\
& \times \exp\left[-kr_o^2\left(\alpha_n + \alpha_m^* + \alpha_l + \alpha_o^*\right)\right] \\
& \times \exp\left[\frac{(kr_o\alpha_n)^2}{\beta_{j1}^2}\right] \exp\left\{\frac{1}{\beta_{j2}^2}\left[kr_o\alpha_m^* \cos\varphi_m \right.\right. \\
& \left.\left. + \frac{kr_o\alpha_n \cos\varphi_n}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right)\right]^2\right\} \\
& \times \exp\left(\frac{1}{\beta_{j3}^2}\left\{\frac{1}{\beta_{j2}^2}\left[\frac{T_j}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) + \frac{1}{\rho_0^2}\right]\right.\right. \\
& \times \left[kr_o\alpha_m^* \cos\varphi_m + \frac{kr_o\alpha_n \cos\varphi_n}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right)\right] \\
& \left.\left. + \frac{T_j kr_o\alpha_n \cos\varphi_n}{\beta_{j1}^2} + kr_o\alpha_l \cos\varphi_l\right\}^2\right) \\
& \times \exp\left(\frac{q_{j4y}^2}{4\beta_{j4}^2}\right) \exp\left\{\frac{1}{\beta_{j2}^2}\left[kr_o\alpha_m^* \sin\varphi_m \right.\right. \\
& \left.\left. + \frac{kr_o\alpha_n \sin\varphi_n}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right)\right]^2\right\} \\
& \times \exp\left(\frac{1}{\beta_{j3}^2}\left\{\frac{1}{\beta_{j2}^2}\left[\frac{T_j}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) + \frac{1}{\rho_0^2}\right]\right.\right. \\
& \times \left[kr_o\alpha_m^* \sin\varphi_m + \frac{kr_o\alpha_n \sin\varphi_n}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right)\right] \\
& \left.\left. + \frac{T_j kr_o\alpha_n \sin\varphi_n}{\beta_{j1}^2} + kr_o\alpha_l \sin\varphi_l\right\}^2\right),
\end{aligned} \tag{5}$$

with

$$\begin{aligned}
q_{j4x} = {} & \frac{1}{\beta_{j3}^2}\left\{\frac{1}{\beta_{j2}^2}\left[\frac{T_j}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) + \frac{1}{\rho_0^2}\right]\right. \\
& \times \left[kr_o\alpha_m^* \cos\varphi_m + \frac{kr_o\alpha_n \cos\varphi_n}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right)\right] \\
& \left. + \frac{T_j kr_o\alpha_n \cos\varphi_n}{\beta_{j1}^2} + kr_o\alpha_l \cos\varphi_l\right\} \\
& \times \left\{\left[\frac{1}{\beta_{j2}^2\beta_{j1}^2\rho_0^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) - \frac{R_j}{\beta_{j2}^2}\right]\right. \\
& \times \left[\frac{2T_j}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) + \frac{2}{\rho_0^2}\right] + \frac{2T_j}{\beta_{j1}^2\rho_0^2} + \left(\frac{1}{2\rho_s^2}\right. \\
& \left.\left. + \frac{2}{\rho_0^2}\right)\right\} + \frac{2}{\beta_{j2}^2}\left[\frac{1}{\beta_{j1}^2\rho_0^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) - R_j\right] \\
& \times \left[kr_o\alpha_m^* \cos\varphi_m + \frac{kr_o\alpha_n \cos\varphi_n}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right)\right] \\
& + \frac{2kr_o\alpha_n \cos\varphi_n}{\rho_0^2\beta_{j1}^2} + 2kr_o\alpha_o^* \cos\varphi_o,
\end{aligned} \tag{6}$$

q_{j4y} is found by replacing the $\cos\varphi_m, \cos\varphi_n, \cos\varphi_l$ and $\cos\varphi_o$ terms in (6) with $\sin\varphi_m, \sin\varphi_n, \sin\varphi_l$ and $\sin\varphi_o$, respectively.

$$\beta_{j1}^2 = k\alpha_n - \frac{ik}{2L} + \frac{1}{4\rho_s^2} + \frac{2}{\rho_0^2} + T_j, \tag{7}$$

$$\beta_{j2}^2 = -\frac{1}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right)^2 + \theta_{j1}^2, \tag{8}$$

$$\beta_{j3}^2 = \varsigma_{j1}^2 - \frac{T_j^2}{\beta_{j1}^2} - \frac{1}{4\beta_{j2}^2}\left[\frac{2T_j}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) + \frac{2}{\rho_0^2}\right]^2, \tag{9}$$

$$\begin{aligned}
\beta_{j4}^2 = {} & \xi_{j1}^2 - \frac{1}{\beta_{j2}^2}\left[\frac{1}{\beta_{j1}^2\rho_0^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) - R_j\right]^2 - \frac{1}{\beta_{j1}^2\rho_0^4} \\
& - \frac{1}{\beta_{j3}^2}\left\{\left[\frac{1}{\beta_{j2}^2\beta_{j1}^2\rho_0^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) - \frac{R_j}{\beta_{j2}^2}\right]\right. \\
& \times \left[\frac{T_j}{\beta_{j1}^2}\left(\frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right) + \frac{1}{\rho_0^2}\right] + \frac{T_j}{\beta_{j1}^2\rho_0^2} \\
& \left. + \frac{1}{4\rho_s^2} + \frac{1}{\rho_0^2}\right\}^2,
\end{aligned} \tag{10}$$

$$\theta_{j1}^2 = k\alpha_m^* + \frac{ik}{2L} + \frac{1}{4\rho_s^2} + \frac{2}{\rho_0^2} - R_j, \tag{11}$$

$$\varsigma_{j1}^2 = k\alpha_l - \frac{ik}{2L} + \frac{1}{4\rho_s^2} + \frac{2}{\rho_0^2} + T_j, \tag{12}$$

$$\xi_{j1}^2 = k\alpha_o^* + \frac{ik}{2L} + \frac{1}{4\rho_s^2} + \frac{2}{\rho_0^2} - R_j, \tag{13}$$

$$E_j = \begin{cases} 1, & \text{for } j = 1 \\ 2\sigma_\chi^2, & \text{for } j = 2, 3 \end{cases}, \tag{14}$$

$$T_j = \begin{cases} \frac{i}{\rho_{\chi S}^2} - \frac{1}{\rho_0^2}, & \text{for } j = 1, 3 \\ \frac{i}{\rho_{\chi S}^2}, & \text{for } j = 2 \end{cases}, \tag{15}$$

$$R_j = \begin{cases} \frac{1}{\rho_0^2} + \frac{i}{\rho_{\chi S}^2}, & \text{for } j = 1, 2 \\ \frac{i}{\rho_{\chi S}^2}, & \text{for } j = 3 \end{cases}, \tag{16}$$

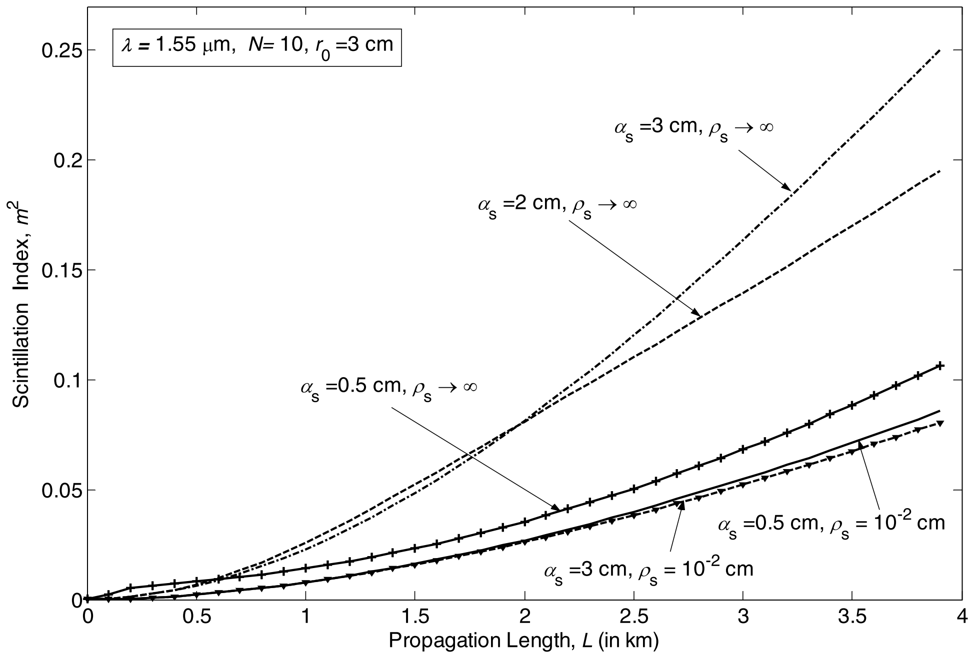


Fig. 1 Dependence of the scintillation index on the source size α_s for partially coherent and coherent laser beam arrays along the propagation axis

where $\rho_{\chi S} = (0.114k^{13/6}C_n^2L^{5/6})^{-1/2}$ is the coherence length of log-amplitude and phase, and $\sigma_\chi^2 = 0.124C_n^2k^{7/6}L^{11/6}$ is the variance of log-amplitude for spherical waves [35].

3 Results and discussions

In this section, using (2), on-axis scintillation indices of coherent and partially coherent laser beam arrays are evaluated and plotted under conditions of weak atmospheric turbulence. For coherent ($\rho_s \to \infty$) and the partially coherent cases, intensity fluctuation variations are analyzed at different source and propagation parameters by letting $\alpha_{sn} = \alpha_{sm} = \alpha_{sl} = \alpha_{so} = \alpha_s$. When $r_o = 0$ and $N = 1$, our results correctly yield the partially coherent Gaussian beam scintillation index values of Refs. [29, 36]. Also, by setting $\frac{r_o \cos\varphi_n}{\alpha_s^2} = -jV_x$, $\frac{r_o \sin\varphi_n}{\alpha_s^2} = -jV_y$ and $N = 2$ in our formulation, we correctly obtain the scintillation index values of the partially coherent off-axis Gaussian beams given in [36].

As already stressed, our theoretical derivation applies to conditions of weak turbulence. Customarily we speak about weak turbulence when the values of k, L and C_n^2 are chosen such that $1.23C_n^2k^{7/6}L^{11/6} < 1$ is satisfied under all circumstances [37]. Accordingly in all our figures, we take $\lambda = 1.55$ μm except in Fig. 4, where the scintillation index variation is examined at different wavelengths, and $C_n^2 = 1 \times 10^{-15}$ m$^{-2/3}$. Figure 1 displays the scintillation index variations of coherent and partially coherent laser beam arrays along the propagation axis for different source sizes. With the settings of $N = 10, r_o = 3$ cm, we observe in Fig. 1 that the scintillation index shows slight reductions with the increasing values of source size for partially coherent laser beam arrays, whereas the opposite happens for coherent laser beam arrays, particularly at longer propagation lengths.

In Fig. 2, the scintillation indices of partially coherent laser beam arrays are illustrated at $N = 5, \alpha_s = 1$ cm, for various values of radial distance parameter r_o along the propagation axis. Figure 2 demonstrates that, for partially coherent laser beam arrays, the scintillation index experiences slight reductions with increasing values of r_o, but this trend is reversed for coherent laser beam arrays, where relatively sharp increases of the scintillation index are seen against the increasing r_o values. For Fig. 2, it is also possible to state that at each propagation length, for the same r_o, the scintillations of partially coherent laser beam arrays are less than the scintillations of coherent laser beam arrays.

In Fig. 3, using the given settings, the effect of the number of beamlets N on the scintillation index is examined along the propagation axis for coherent and partially coherent beams. It is observed from Fig. 3 that, as laser beam arrays become less coherent, the increasing values of N makes the scintillation index lower but only slightly. For this partially coherent case, the scintillation index reductions are barely noticeable beyond $N \geq 2$. For the coherent case of Fig. 3, the smallest scintillations are attained at $N = 1$. Although scintillations become maximized when $N = 2$, they become smaller and merge into the same curve for all other larger N values.

Figure 4 displays the dependence of the scintillation index of partially coherent laser beam arrays on the wavelength of operation λ along the propagation axis. According

Fig. 2 Dependence of the scintillation index on the radial displacement parameter r_o for partially coherent and coherent laser beam arrays along the propagation axis

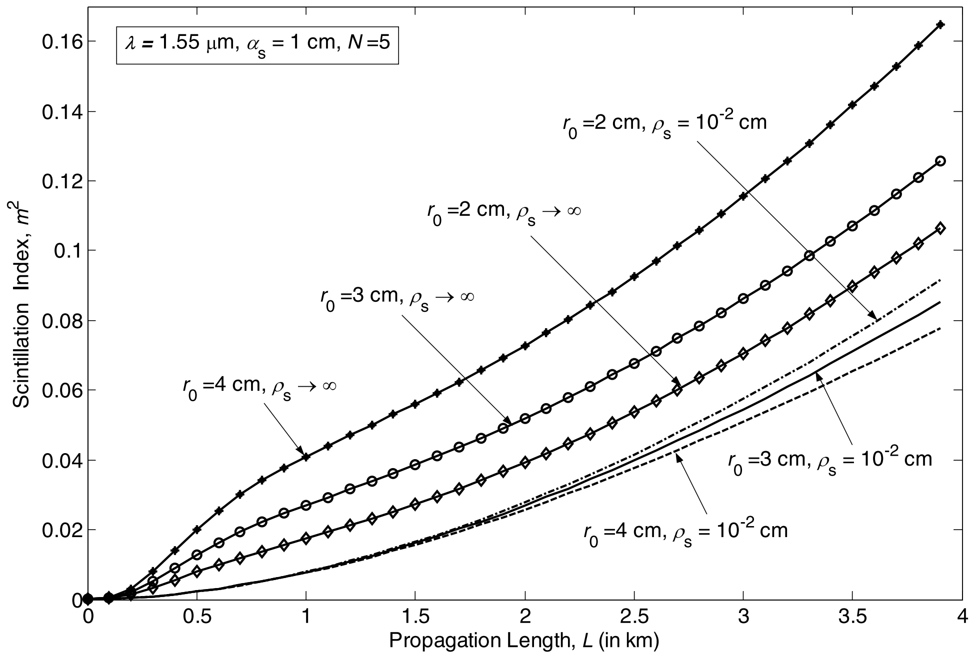
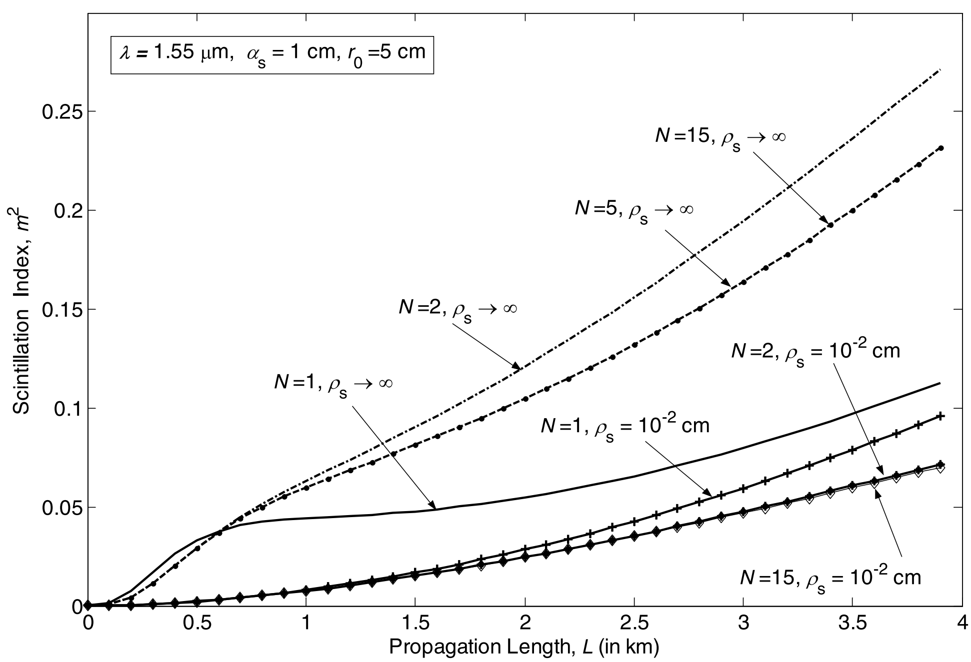


Fig. 3 Dependence of the scintillation index on the number of beamlets N for partially coherent and coherent laser beam arrays along the propagation axis



to Fig. 4, with rises in wavelength there will be a fall in the scintillation indices of both partially coherent and coherent laser beam arrays, where the latter observation is in line with our previous findings [11].

When Figs. 1–4 are considered all together, it is possible to conclude that the scintillation index of partially coherent laser beam arrays is lower than the scintillation index of coherent laser beam arrays. This is further confirmed by Fig. 5, where it is clearly demonstrated that, as the level of coherence ρ_s is lowered, the scintillation index of partially coherent laser beam arrays gradually drops from its highest curve of full coherence.

In Fig. 6, the dependence of the scintillation index on ρ_s is explored along the axis of source size. Toward full coherence, the scintillation index seems to rise with increasing source sizes, then a downward trend is encountered, but with escalating partial coherence this behavior turns into a flatter curve where eventually almost no scintillation changes against the growing source sizes are detected. It is observed in Fig. 6 that the scintillation index decreases at large source

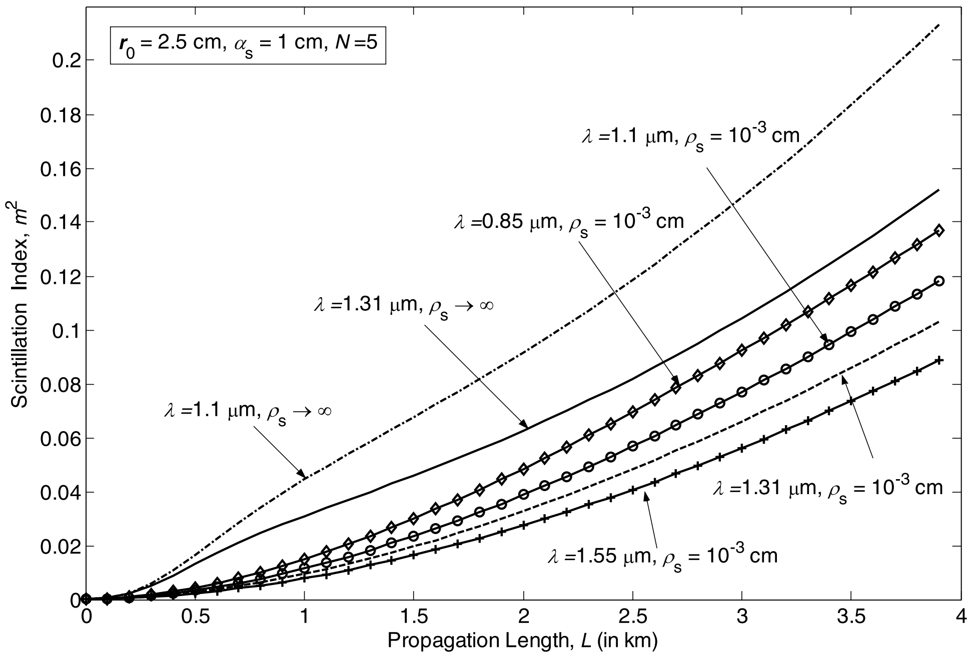


Fig. 4 Dependence of the scintillation index on the wavelength of operation λ for partially coherent and coherent laser beam arrays along the propagation axis

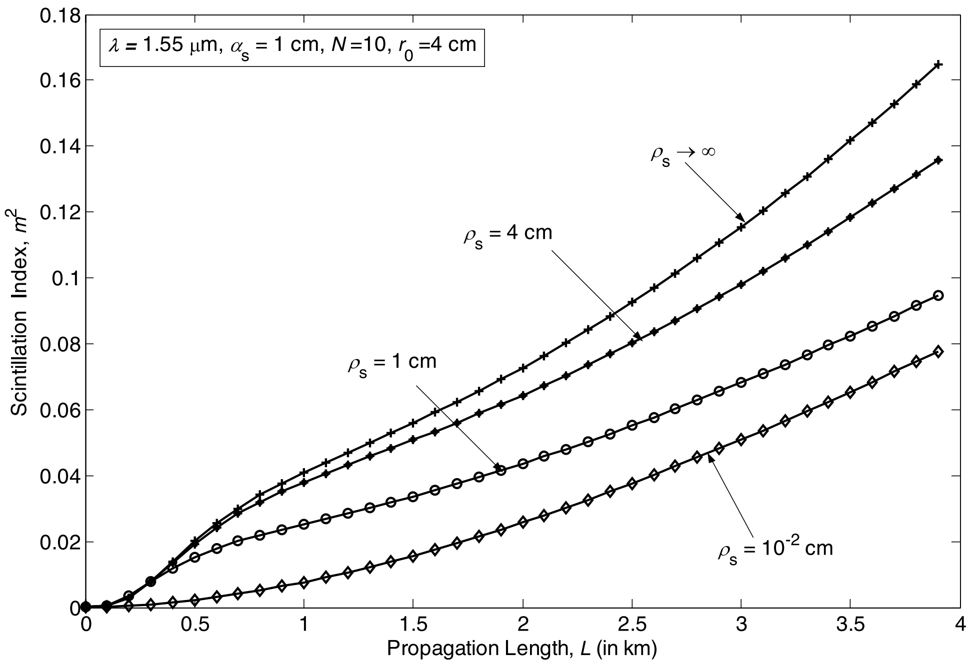


Fig. 5 Dependence of the scintillation index on the degree of coherence ρ_s along the propagation axis

sizes if the laser beam array is less coherent. Here we note that, in practice, the scintillation index is not the only criterion but the beam spreading should also be considered. However, in the current paper our interest is limited to scintillation effects.

4 Concluding remarks

Based on the extended Huygens–Fresnel principle, an analytical formula is derived for the on-axis intensity fluctuations of partially coherent laser beam arrays in weak atmospheric turbulence. By using the derived formula we have investigated the dependence of the scintillation index of the phase-locked radial partially coherent laser beam arrays on the source and propagation parameters such as the propagation distance, source size, radial distance, wavelength of operation, number of beamlets and level of coherence. The scintillation indices of coherent laser beam arrays are also plotted and compared to partially coherent cases. Our graphical results reveal that at partial coherence levels larger source sizes help the scintillation index reduce slightly, but

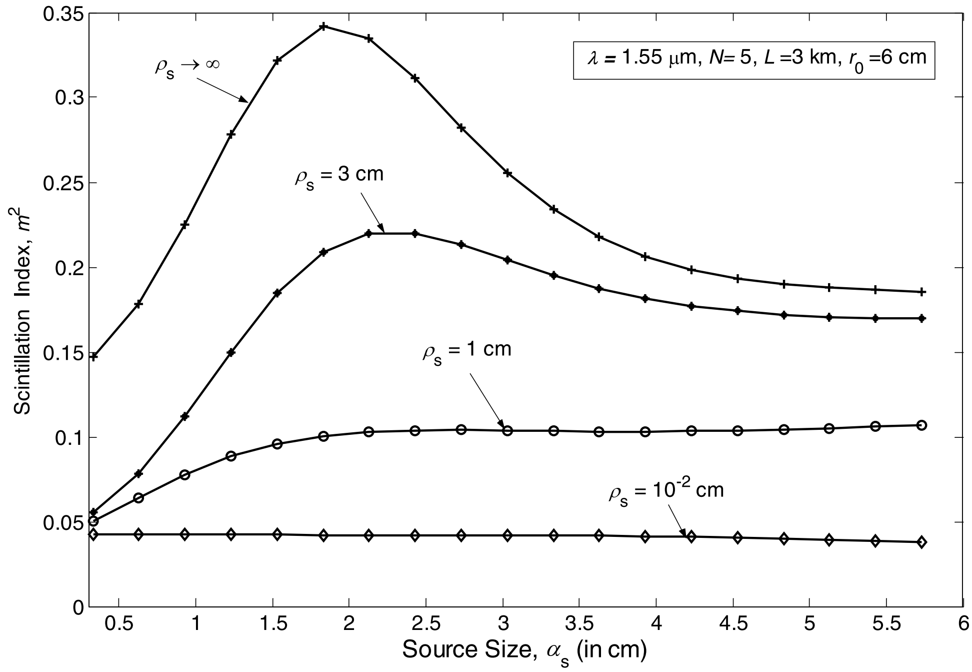


Fig. 6 Dependence of the scintillation index on the degree of coherence ρ_s along the source size axis

at full coherence levels the reverse will occur. A similar phenomenon will be observed for the radial distance parameter that is in partial coherence; rises in the radial displacement parameter will cause small drops in the scintillation index, but greater increases of scintillations will occur at full coherence levels against the rising radial distance. The increasing number of beamlets appears to reduce scintillations at partial coherence levels, but its effect is felt more at full coherence, where the lowest scintillations are found for a single beam. In line with previous findings, longer wavelengths offer less scintillations. Examination of the scintillation index versus the source size reveals that initially there will be increases of the scintillations with growing source sizes, then a downward trend will be observed, particularly toward full coherence, but at escalating partial coherence levels this behavior will eventually disappear, leading to a flat curve with no changes observable in scintillation index against source size variations.

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